

## BLACK HOLE SPIN IN X-RAY BINARIES: OBSERVATIONAL CONSEQUENCES

S. N. ZHANG,<sup>1,2</sup> WEI CUI,<sup>3</sup> AND WAN CHEN<sup>4,5</sup>

Received 1997 February 5; accepted 1997 April 8

### ABSTRACT

We discuss the observational consequences of black hole spin in X-ray binaries within the framework of the standard thin accretion disk model. When compared with theoretical flux distribution from the surface of a thin disk surrounding a Kerr black hole, the observed X-ray properties of the Galactic superluminal jet sources, GRO J1655–40 and GRS 1915+105, strongly suggest that each contains a black hole spinning rapidly in the same direction as the accretion disk. We show, however, that some other black hole binaries with an ultrasoft X-ray component probably harbor only non- or slowly spinning black holes, and we argue that those with no detectable ultrasoft component above 1–2 keV in their high luminosity state may contain a fast-spinning black hole but with a retrograde disk. Therefore, all classes of known black hole binaries are united within one scheme. Furthermore, we explore the possibility that spectral state transitions in Cyg X-1 are simply due to temporary disk reversal, which can occur in a wind accretion system.

*Subject headings:* black hole physics — X-rays: stars

### 1. INTRODUCTION

Significant progress has been made in recent years in observations of Galactic black hole binaries (BHBs) (see Tanaka & Lewin 1995 for a review). Optical studies show that the dynamic mass of the compact object in many black hole candidates (BHCs) is well above  $3 M_{\odot}$ , the upper limit on the mass of neutron stars. BHCs are so classified because of the similarity of their X-ray properties to those of Cyg X-1, the first dynamically proven BH with  $M > 7M_{\odot}$ . Such similarity includes the presence of an ultrasoft spectral component with a characteristic blackbody (BB) temperature of 0.5–2 keV and an underlying power-law hard tail that extends beyond 100 keV. Both are rarely seen from NS binaries.

The ultrasoft component is emitted from the inner region of the accretion disk, close to the BH horizon. The origin of the hard tail is still unclear but is believed to be related to the lack of a solid surface on BHs and the strong gravitational field near the horizon. Systematic optical studies of BHCs selected based on these criteria have been very successful in finding compact objects with masses greater than  $3 M_{\odot}$ .

However, an ultrasoft component of 0.5–1.0 keV is absent in the bright-state X-ray spectra of at least 5 (GS 2023+338, GRO J0422+32, GRO J1719–24, 1E 1740.7–2942, and GRS 1758–258) of about two dozen known BHCs. Neither is it observed in Cyg X-1 and GX 339–4 when they are in the so-called hard (or low) state. Both GS 2023+338 and GRO J0422+32 are dynamically confirmed BHBs. It is thus an outstanding puzzle why the ultrasoft component is missing in their X-ray spectra. None of these sources is an eclipsing system, so the outer edge of the disk is not likely to block radiation from the inner disk.

In this letter, we suggest that the strength of the ultrasoft component is directly related to the BH spin. The presence (or absence) of such a component would, therefore, depend critically on the specific angular momentum of the BH and the

orientation of its spin axis with respect to that of the accretion disk.

### 2. DISK EMISSION FROM A KERR BLACK HOLE BINARY

We assume a geometrically thin, optically thick accretion disk (Novikov & Thorne 1973; Shakura & Sunyaev 1973) orbiting a Kerr BH in the equatorial plane. The BH spin affects the properties of the inner disk region in at least two ways (Bardeen, Press, & Teukolsky 1972). First, the radius of a Kerr BH horizon,  $r_h$ , is smaller than that of a nonspinning BH,  $r_h = r_g + (r_g^2 - a^2)^{1/2} = r_g[1 + (1 - a_*^2)^{1/2}]$ , where  $r_g = GM/c^2$  ( $M$  is the BH mass),  $a = J/Mc$  ( $J$  is the BH angular momentum). The dimensionless specific angular momentum,  $a_* = a/r_g$ , varies from  $-1$  to  $1$ . For maximally spinning BHs,  $|a_*| = 1$  and  $r_h$  ( $a_* = \pm 1$ ) =  $r_g = 0.5r_h(a_* = 0)$ . Second, the radius of the last (marginally) stable orbit of the accretion disk is a function of the BH spin, i.e.,

$$r_{\text{last}} = r_g \{3 + A_2 \pm [(3 - A_1)(3 + A_1 + 2A_2)]^{1/2}\}, \quad (1)$$

where  $A_1 = 1 + (1 - a_*^2)^{1/3}[(1 + a_*)^{1/3} + (1 - a_*)^{1/3}]$ ,  $A_2 = (3a_*^2 + A_1^2)^{1/2}$ ; the lower and upper signs are for a prograde disk (i.e., rotating in the same direction of the BH, or  $a_* > 0$ ) and a retrograde disk ( $a_* < 0$ ), respectively. Therefore, a disk around a Kerr BH may extend all the way in to the horizon,  $r_{\text{last}}(a_* = 1) = r_g$  or be expelled to  $r_{\text{last}}(a_* = -1) = 9r_g$ , as compared with the canonical Schwarzschild case,  $r_{\text{last}}(a_* = 0) = 6r_g$ .

The local gravitational energy release per unit area from the surface of the disk is also a function of the BH spin (Page & Thorne 1974),

$$F(x) = \frac{3\dot{M}c^6}{8\pi M^2 G^2 x^4} \frac{1}{(x^3 - 3x + 2a_*)} \times \left[ x - x_0 - \frac{3}{2} a_* \ln \left( \frac{x}{x_0} \right) - \frac{3(x_1 - a_*)^2}{x_1(x_1 - x_2)(x_1 - x_3)} \times \ln \left( \frac{x - x_1}{x_0 - x_1} \right) - \frac{3(x_2 - a_*)^2}{x_2(x_2 - x_1)(x_2 - x_3)} \ln \left( \frac{x - x_2}{x_0 - x_2} \right) - \frac{3(x_3 - a_*)^2}{x_3(x_3 - x_1)(x_3 - x_2)} \ln \left( \frac{x - x_3}{x_0 - x_3} \right) \right], \quad (2)$$

where  $\dot{M}$  is the mass accretion rate,  $x = (r/r_g)^{1/2}$ ,  $x_0 = (r_{\text{last}}/r_g)^{1/2}$ ,  $x_1 = 2 \cos(1/3 \cos^{-1} a_* - \pi/3)$ ,  $x_2 = 2 \cos(1/3$

<sup>1</sup> ES-84, NASA/Marshall Space Flight Center, Huntsville, AL 35812; zhang@ssl.msfc.nasa.gov.

<sup>2</sup> Universities Space Research Association.

<sup>3</sup> Room 37-571, Center for Space Research, Massachusetts Institute of Technology, Cambridge, MA 02139; cui@space.mit.edu.

<sup>4</sup> Department of Astronomy, University of Maryland, College Park, MD 20742.

<sup>5</sup> NASA/Goddard Space Flight Center, Code 661, Greenbelt, MD 20771; chen@milkyway.gsfc.nasa.gov.

TABLE 1  
GENERAL RELATIVISTIC CORRECTION FACTORS TO THE LOCAL  
DISK SPECTRUM

$\theta$	$\cos \theta$	$a_* = 0.0$		$a_* = 0.998$	
		$g(\theta, a_*)$	$f_{GR}(\theta, a_*)$	$g(\theta, a_*)$	$f_{GR}(\theta, a_*)$
0.0....	1.00	0.797	0.851	0.328	0.355
41.4....	0.75	0.654	0.870	0.344	0.587
60.0....	0.50	0.504	0.981	0.359	0.764
75.5....	0.25	0.289	1.058	0.352	1.064
90.0....	0.00	0.036	1.354	0.206	1.657

NOTE.—The table is derived from Cunningham (1975).  $a_* = 0.998$  corresponds to the maximally prograde systems. In the Newtonian limit of  $g(\theta, a_*) = \cos \theta$  and  $f_{GR}(\theta, a_*) = 1$ .

$\cos^{-1}a_* + \pi/3$ ), and  $x_3 = -2 \cos(1/3 \cos^{-1}a_*)$ . From equation (2), the effective BB temperature of the disk,  $T(x) = [F(x)/\sigma]^{1/4}$ , with  $\sigma$  being the Stefan-Boltzmann constant, actually peaks at an annulus slightly beyond  $r_{\text{last}}$ : i.e.,  $r_{\text{peak}} = r_{\text{last}}/\eta$ , and  $\eta$  varies slowly from 0.63 to 0.77 for  $a_*$  from  $-1$  to  $1$ .

The observed disk spectrum, however, bears several important corrections to this simple formula. First, on the hot inner disk where most X-rays are emitted, electron scattering may dominate over the free-free absorption and so causes the color temperature to be greater than the effective temperature (Ross, Fabian, & Mineshige 1992). As a result, the inner disk radiates approximately like a “diluted” BB,  $B(E, f_{\text{col}}(x)T(x))/[f_{\text{col}}(x)]^4$  (Ebisuzaki, Hanawa, & Sugimoto 1984), where  $B(E, f_{\text{col}}(x)T(x))$  is the Planck function and  $f_{\text{col}}(x)$  is the color correction factor. Detailed calculations (Shimura & Takahara 1995), including general relativistic effects, show that  $f_{\text{col}}(x)$  depends only very weakly on  $x$ , so that it can be approximated by a constant  $f_{\text{col}}$ . Furthermore,  $f_{\text{col}}$  depends weakly on  $M$  and  $\dot{M}$ , such that  $f_{\text{col}} = 1.7 \pm 0.2$  for  $1.4 \leq M/M_{\odot} \leq 10$  and  $0.1 \leq \dot{M}/\dot{M}_{\text{Edd}} \leq 10$ , where  $\dot{M}_{\text{Edd}}$  is the Eddington accretion rate. Therefore, the dependence of  $f_{\text{col}}$  on  $a_*$ , although unknown, should also be weak, and we adopt  $f_{\text{col}} = 1.7$  in this paper.

The second important correction is due to general relativistic (GR) effects near the BH horizon, e.g., the gravitational redshifts and focusing, which cause both the observed color temperature and integrated flux to deviate from the local values, depending on the inclination angle of the disk,  $\theta$ , and the BH spin (Cunningham 1975). Here we introduce two additional correction factors,  $f_{GR}(\theta, a_*)$ —the fractional change of the color temperature, and  $g(\theta, a_*)$ —the additional change of the integrated flux due to viewing angle and GR effects. We note that in the Newtonian limit  $g(\theta, a_*) = \cos \theta$ , so the pure GR effect on the observed flux is  $g_{GR} = g(\theta, a_*)/\cos \theta$ . From Cunningham (1975), we derive these correction factors for several viewing angles and for  $a_* = 0$  and 0.998. The results are listed in Table 1. The calculations at  $a_* = 0.998$  are for prograde disks. Retrograde disks should produce lesser effects than the  $a_* = 0$  case. It is clear that the GR effects cause (1) the spectrum to be redshifted at small  $\theta$  but blueshifted at large  $\theta$ , (2) the flux to be smaller than the Newtonian flux at small  $\theta$  but greater at large  $\theta$  (gravitational focusing), and (3) the spin of the BH to induce even larger deviation.

There is a simple relation between the bolometric luminosity of the disk and the peak emission region,  $L_{\text{disk}} \approx 4\pi\sigma^2 r_{\text{peak}}^2 T_{\text{peak}}^4$  (Makishima et al. 1986). We note that  $L_{\text{disk}}$  depends on both  $\dot{M}$  and  $a_*$  but not on  $M$ . Our numerical integrations over equation (2) confirm that the above relation is accurate to within 10% for a wide range of the parameter space. Including the temperature and flux corrections we introduced above, the observed flux is related to the local disk

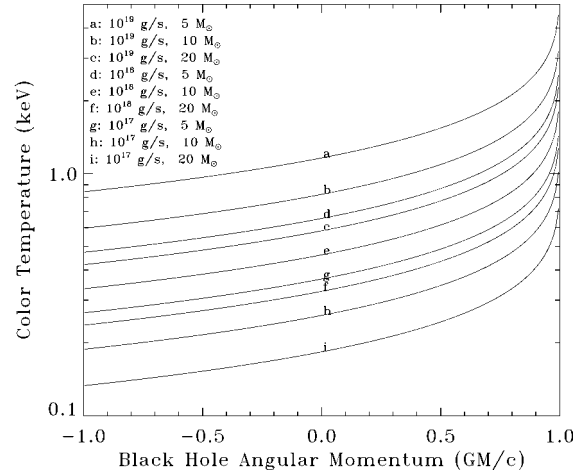


FIG. 1.—The peak color temperature ( $kT_{\text{col}}$ ) of the accretion disk emission as a function of the dimensionless specific angular momentum ( $a_*$ ) of the Kerr BH, for several mass accretion rates and BH masses.

luminosity by  $F_{\text{earth}} = g(\theta, a_*)L_{\text{disk}}/2\pi D^2$ , and the observed color temperature is  $T_{\text{col}} = f_{GR}(\theta, a_*)f_{\text{col}}T_{\text{peak}}$ . Therefore, the inner disk radius,  $r_{\text{last}}$ , for a source at distance  $D$  can be derived as

$$r_{\text{last}} = \eta D \left[ \frac{F_{\text{earth}}}{2\sigma g(\theta, a_*)} \right]^{1/2} \left[ \frac{f_{\text{col}} f_{GR}(\theta, a_*)}{T_{\text{col}}} \right]^2. \quad (3)$$

Combining equations (1) and (3), one can thus solve for both  $r_{\text{last}}$  and  $a_*$ , if  $M_{\text{BH}}$  and  $\theta$  are known. The largest theoretical uncertainty in equation (3) is from  $f_{\text{col}}$  for prograde Kerr BHs. Based on our discussion above, however, the uncertainty in  $f_{\text{col}}$  is  $\sim 10\%$ , which will cause an error of no more than 20% in  $r_{\text{last}}$ .

Therefore, the spin of a BH may strongly influence both the disk color temperature and the disk luminosity we observed, as illustrated in Figures 1 and 2, for typical  $M_{\text{BH}}$  and  $\dot{M}$ . We see that prograde BHBs will usually have a higher color temperature than the nonspinning systems, while retrograde BHBs, especially the more massive ones, will have a softer disk component, which may in many cases escape our detection. On the other hand, the conversion efficiency of the gravitational energy to radiation,  $L_{\text{disk}}/\dot{M}c^2$ , is a function of  $a_*$  only and increases parabolically from  $\sim 3\%$  to  $\sim 30\%$  as  $a_*$  changes from  $-1$  to  $1$ ; it is  $\sim 6\%$  for a Schwarzschild BH (Thorne 1974). To be in line with most X-ray observations, in Figure 2

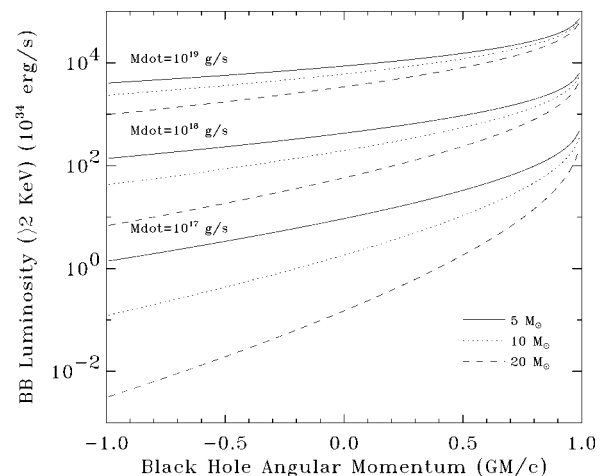


FIG. 2.—The ultrasoft component (disk blackbody) luminosity above 2 keV, as a function of  $a_*$ , for several mass accretion rates and black hole masses.

we plot the disk luminosity above 2 keV,  $L_D (>2 \text{ keV})$  as a function of  $a_*$ .

### 3. CLASSIFICATION OF BLACK HOLE BINARIES BY BLACK HOLE SPIN

Figures 1 and 2 show that the accretion disk spectrum of a BHB becomes distinctively different only when the BH spins extremely rapidly. It is thus natural to classify BHBs into three groups, namely, extreme prograde systems ( $a_* \lesssim 1$ ), non- or slowly spinning systems ( $|a_*| \simeq 0$ ), and extreme retrograde systems ( $a_* \gtrsim -1$ ).

*Extreme prograde systems.* This class currently includes GRO J1655–40 and possibly GRS 1915+105, which are the only two known Galactic superluminal jet sources. For GRO J1655–40, its  $M_{\text{BH}}$  and  $\theta$  have been optically determined as  $7.02 \pm 0.22 M_\odot$  and  $69.5 \pm 0.08$  (Orosz & Bailyn 1997). Spectral fitting to its *Advanced Satellite for Cosmology and Astrophysics (ASCA)* X-ray spectrum during its 1995 August outburst gives  $kT_{\text{col}} = 1.36 \text{ keV}$  and an unabsorbed BB flux of  $3.3 \times 10^{-8} \text{ ergs s}^{-1} \text{ cm}^{-2}$  (Zhang et al. 1997a). Applying equation (3) to a Schwarzschild BH with  $\eta = 0.7$ ,  $g = 0.368$ , and  $f_{\text{GR}} = 1.03$ , we derive an inner disk radius of  $r_{\text{last}} = 23.3 \text{ km}$ , or  $2.3r_g$  for a  $7 M_\odot$  BH. We note that all the observables have very small statistical errors, and for a Schwarzschild BH the quoted  $f_{\text{col}}$  and  $f_{\text{GR}}(\theta, a_*)$  are exact; the inferred  $r_{\text{last}}$  for GRO J1655–40 thus contains at most 10% error. Therefore, it will be extremely difficult to reconcile the discrepancy between the observed  $r_{\text{last}}$  and the theoretical minimum of  $6r_g$  for a nonspinning BH.

The simplest solution is to assume that the BH in GRO J1655–40 is spinning. Solving equations (1) and (3) self-consistently with  $\eta = 0.76$ ,  $g = 0.354$ , and  $f_{\text{GR}} = 0.954$ , we find that  $r_{\text{last}} = 22.1 \text{ km}$  and  $a_* = 0.93\%$ . Although we have used values of  $g$  and  $f_{\text{GR}}$  for  $a_* = 0.998$  and  $f_{\text{col}} = 1.7$  in the calculation, based on our above discussion the lower limit to  $a_*$  is 0.7. Therefore we conclude that GRO J1655–40 most probably contains a Kerr BH spinning at between 70% and 100% (most likely a value of 93%) of the maximum rate.

We note that the  $a_*$  derived above is actually consistent with that inferred independently from the X-ray timing data. A high-frequency quasi-periodic oscillation (QPO) of  $\sim 300 \text{ Hz}$  was observed in GRO J1655–40 (Remillard 1997). One of its possible origins is the trapped  $g$ -mode oscillations near the inner edge of the disk (Okazaki, Kato, & Fukue 1987). By including the GR effects, Perez et al. (1997) show that the fundamental frequency of the radial modes is given by  $f \approx 714(M_\odot/M)F(a_*)$ . If the  $\sim 300 \text{ Hz}$  QPO is indeed due to this mode, then  $F(a_*) = 2.94$ , which corresponds to  $a_* = 0.95$ , in agreement with our result. It is, however, not clear how such models can explain why the QPO is more prominent at higher energies and why it is observed only when the energy spectrum becomes the hardest (Remillard 1997).

The case for GRS 1915+105 is less straightforward because its BH mass is unknown. However, this source also has a similar BB component and a high-frequency QPO during its recent outburst. We can estimate the radius of the inner edge of the disk using its X-ray spectrum and then, by assuming the observed QPO is also due to the fundamental  $g$ -mode radial oscillations, derive the BH spin self-consistently. Given  $T_{\text{col}} \simeq 2.27 \text{ keV}$  and  $F_{\text{earth}} = 4.4 \times 10^{-8} \text{ ergs s}^{-1} \text{ cm}^{-2}$  (Belloni et al. 1997), the inner disk radius is  $\sim 40 \text{ km}$ , for a distance of 12.5 kpc and  $\theta = 70^\circ$  (Mirabel & Rodriguez 1994). This implies a Schwarzschild BH mass of  $\sim 4.5 M_\odot$  or an extreme Kerr BH mass of  $\sim 27 M_\odot$  with a prograde disk. On the other hand,

TABLE 2

THE INFERRED BLACK HOLE SPIN IN SEVERAL BLACK HOLE BINARIES

Source	$M$ ( $M_\odot$ )	$\theta$ (deg)	$D$ (kpc)	$kT_{\text{col}}$ (keV)	$r_{\text{last}}$ (km)	$a_*$
GS 1124–68 <sup>a</sup> .....	6.3	60	2.0	1.0	57	–0.04
GS 2000+25 <sup>b</sup> .....	10	65	2.5	1.2	86	0.03
LMC X-3 <sup>c</sup> .....	7	60	50	1.2	69	–0.03
GRO J1655–40 <sup>d</sup> ...	7	70	3.2	1.4	22	0.93
GRS 1915+105 <sup>e</sup> ....	$\sim 30$	70	12.5	2.2	40	$\sim 0.998$

<sup>a</sup> From Orosz et al. 1996.

<sup>b</sup> From Callanan et al. 1996.

<sup>c</sup> From Cowley et al. 1983.

<sup>d</sup> From Orosz & Bailyn 1997.

<sup>e</sup> From Mirabel & Rodriguez 1994.

applying the trapped  $g$ -mode model to the  $\sim 67 \text{ Hz}$  QPO (Morgan, Remillard, & Greiner 1996, 1997) yields  $M \sim 11 M_\odot$  for a nonspinning BH and  $M \sim 36 M_\odot$  for an extreme prograde Kerr BH (Nowak et al. 1997). The consistency between these two approaches thus suggests that GRS 1915+105 may contain a Kerr BH of  $\sim 30 M_\odot$ , which is also spinning near the maximum rate.

*Non- or slowly spinning systems.* There are several BHBs whose inner disk radii have been reliably measured based on their bright-state X-ray spectra (e.g., Tanaka & Lewin 1995), and their  $M$  and  $\theta$  have also been determined optically. We use equation (1) to calculate their  $a_*$ , and the results are listed in Table 2, which also includes the two superluminal jet sources. In contrast to GRO J1655–40, these sources show little sign of BH spin.

While the theoretical uncertainties in  $r_{\text{last}}$  for nonspinning BHs are small, the observational uncertainties in  $\theta$  and  $M$  for these systems are greater than those for GRO J1655–40. It is still intriguing to see that the BHs in these BHBs *appear* to be spinning slowly. This is consistent with the fact that the three nominal BHBs all have a lower  $T_{\text{col}}$  than the two superluminal sources. Figure 2 shows that when other system parameters are equal, a prograde disk at  $a_* \sim 1$  always has a higher  $T_{\text{col}}$  than the disk at  $a_* \sim 0$  since  $r_{\text{last}} \propto T_{\text{col}}^{-2}$ . Thus, although their system parameters are mostly unknown, most of other ultrasoft BHBs listed in Table 3-1 of Tanaka & Lewin (1995) may also be slow-spinning BHBs. We do not know, though, if they are slow spinners at birth, or if they have been slowed down, or if their spin axis simply lies close to the disk plane.

*Extreme retrograde systems.* The absence of a detectable ultrasoft component above 1–2 keV in the X-ray bright state could imply an even softer disk spectrum of  $kT_{\text{col}} < 0.3 \text{ keV}$ . If so, such a BHB will likely contain an extreme Kerr BH with a retrograde disk (Fig. 1). While there is yet no proof that they are, we postulate that GRO J1719–24, GS 2023+338, and GRO J0422+32 are such Kerr BH systems. The existence of the extreme retrograde BHBs can be confirmed unambiguously only when one detects a weak ultrasoft component at a lower temperature from those sources in their bright outburst state. A reliable detection will not be easy, though, because it requires an adequate detector response down to 0.1 keV and a small interstellar absorption column.

### 4. SPECTRAL STATE TRANSITIONS OF CYG X-1

Cyg X-1 is a particularly interesting source in our accreting Kerr BH picture because it shows the characteristics of *both* a prograde and a retrograde BHB. This is mainly related to its distinctive spectral state transitions, whose nature has not been understood properly. Many models suggest that the state

transitions are accompanied by significant  $\dot{M}$  changes, in conflict with recent observations that showed approximately constant total luminosity throughout the state transitions (Zhang et al. 1997b). Another misconception is that the X-ray spectrum of Cyg X-1 in its hard state always contains *only* a power law with an energy spectral index of 0.5–1.0 and a spectral break at 50–100 keV. Recently, however, a very low temperature BB component was clearly detected by *ROSAT* (Balucinska-Church et al. 1995) and confirmed by *ASCA* (Ebisawa et al. 1996), with  $kT_{\text{col}} \sim 0.1\text{--}0.2$  keV and an estimated luminosity of  $\sim 5 \times 10^{36}$  ergs  $\text{s}^{-1}$ . According to Figures 1 and 2 for  $\dot{M}$  of  $10\text{--}20 M_{\odot}$  and  $\dot{M}$  of  $10^{17}\text{--}10^{18}$  g  $\text{s}^{-1}$ , the observed low-temperature BB component clearly suggests a retrograde system. On the other hand, observations in 1996 indicate that the inner disk radius dropped by a factor of 2–3 and  $\dot{M}$  increased by less than a factor of 2 when Cyg X-1 changed from the hard to the soft state (Zhang et al. 1997b).

The inner disk radius in Cyg X-1 is likely always at the last stable orbit since  $\dot{M}$  is always high. If so, we find that the observed decrease of  $r_{\text{last}}$  during the hard-to-soft transition can be simply explained by the *reversal* of the disk rotation from a retrograde disk to a prograde disk or, quantitatively, by  $a_*$  switching from  $-0.75$  to  $0.75$ . A smaller  $r_{\text{last}}$  also causes an increase of the observed  $T_{\text{col}}$  by a factor of  $\sim 2.5$  and of the observed  $L_{\text{disk}}$  by a factor of  $\lesssim 6$  (Figs. 1 and 2). If the BH were not spinning, the temperature increase would require a significant increase in  $\dot{M}$ , so that the BB luminosity would have jumped by a factor of 40, which is not seen in the observations.

## 5. DISCUSSION

In summary, all the observed BHBs can be unified within the framework that the BH in a binary system may spin up to the maximally allowed speed and both prograde and retrograde systems exist. The two Galactic superluminal jet sources are the only known rapidly prograde systems so far, implying that the formation of the relativistic jets is perhaps related to both the rapid spin of the BH and the prograde configuration. The majority of other known ultrasoft BHBs appear to contain slowly spinning BHs. We have also suggested that the BHBs without any detectable ultrasoft component above 2 keV may be extreme Kerr BHBs with retrograde disks.

The canonical BHB Cyg X-1 may actually switch from a retrograde system in its normal hard (or low) state to a prograde system in the soft (or high) state, when the accretion disk reverses its rotation direction temporarily, due to possibly the unstable nature of the wind accretion from its supergiant

massive companion. Although it may sound absurd at first, the accretion disk reversal is actually not at all surprising for Cyg X-1 because it is a wind-accreting system. Two- and three-dimensional numerical simulations show that the flip-flop of an accretion disk rotation can indeed occur in such systems (e.g., Matsuda, Inoue, & Sawada 1987; Benensohn, Lamb, & Taam 1997; Ruffert 1997). The concept of disk reversal, however, cannot be applied to low-mass BHBs, such as GS 1124–683, because their accretion material from Roche lobe overflow gets a strong preference of rotation from the orbital motion. The state transitions in these systems, often accompanied by significant  $\dot{M}$  changes, are therefore due to entirely different mechanisms. Perhaps the lower  $\dot{M}$  causes the inner accretion disk to be truncated in the quiescent (hard) state and forms advection-dominated accretion flow (e.g., Narayan & Yi 1995). In all our calculations, we consider only the high  $\dot{M}$  state in which we believe the accretion disk extends to the last stable orbit.

We have up to this point carefully avoided discussion of hard X-ray production in BHBs. It is worth noting, however, that the hard X-ray luminosity of a prograde system is, on average, much lower than that of a retrograde system. This seems to imply that the hard-X-ray-emitting region is related to the volume between the inner disk boundary and the BH horizon. For Cyg X-1 in the soft state, its hard X-ray luminosity ( $>20$  keV) is about a factor of 10–20 lower for the observed shrinkage of the inner disk radius by a factor of 2–3. So, the hard X-ray luminosity seems to be roughly proportional to the volume inside  $r_{\text{last}}$ .

*Note added in manuscript.*—After this paper was submitted, Nick White pointed out to us that Shapiro & Lightman (1976) had discussed the possibility that the state transitions of Cyg X-1 are due to reversal of the disk rotation for a marginally stable, wind-fed disk around a spinning black hole, an idea originally suggested by J. I. Katz in a private communication (1975). From the observed luminosity change and the expected radiation efficiency change due to disk reversal, they inferred a black hole spin rate of  $a_* \approx 0.9$ , as compared with our result of  $\sim 0.75$ , in which we used the most recent data and also included the expected BB temperature change.

We thank G. J. Fishman, B. A. Harmon, J. van Paradijs, K. Ebisawa, N. White, and R. Remillard for many interesting discussions. van Paradijs and White deserve special mention for carefully reading the manuscript and providing many valuable suggestions.

## REFERENCES

- Balucinska-Church, M., et al. 1995, *A&A*, 302, L5  
 Bardeen, J. M., Press, W. H., & Teukolsky, S. A. 1972, *ApJ*, 178, 347  
 Belloni, T., et al. 1997, *ApJ*, 479, 145  
 Benensohn, J. S., Lamb, D. Q., & Taam, R. E. 1997, *ApJ*, 478, 723  
 Cowley, A. P., et al. 1983, *ApJ*, 272, 118  
 Callanan, P. J., et al. 1996, *ApJ*, 470, L57  
 Cunningham, C. T. 1975, *ApJ*, 202, 788  
 Ebisawa, K., Ueda, Y., Inoue, H., Tanaka, Y., & White, N. E. 1996, *ApJ*, 467, 419  
 Ebisuzaki, T., Hanawa, T., & Sugimoto, D. 1984, *PASJ*, 36, 551  
 Okazaki, A. T., Kato, S., & Fukue, J. 1987, *PASJ*, 39, 457  
 Makishima, K., et al. 1986, *ApJ*, 308, 635  
 Matsuda, T., Inoue, M., & Sawada, K. 1987, *MNRAS*, 226, 785  
 Mirabel, I. F., & Rodriguez, L. F. 1994, *Nature*, 371, 46  
 Morgan, E., Remillard, R., & Greiner, J. 1996, *IAU Circ.* 6392  
 ———, 1997, *ApJ*, 482, 993  
 Narayan, R., & Yi, I. 1995, *ApJ*, 444, 231  
 Novikov, I. D., & Thorne, K. S. 1973, in *Black Holes*, ed. C. DeWitt & B. DeWitt (New York: Gordon & Breach), 343  
 Nowak, M. A., Wagoner, R. V., Begelman, M. C., & Lehr, D. E. 1997, *ApJ*, 477, L91  
 Orosz, J. A., & Bailyn, C. D. 1997, 477, 876  
 Orosz, J. A., et al. 1996, *ApJ*, 468, 380  
 Page, D. N., & Thorne, K. S. 1974, *ApJ*, 191, 499  
 Perez, C. A., Silbergleit, A. S., Wagoner, R. V., & Lehr, D. E. 1997, *ApJ*, 476, 589  
 Remillard, R. 1997, in *Texas in Chicago, Texas Symp. Relativistic Astrophys.* 18, ed. A. Olinto, J. Frieman, & D. Schramm (Singapore: World Scientific), in press  
 Ross, R. R., Fabian, A. C., & Mineshige, S. 1992, *MNRAS*, 258, 189  
 Ruffert, M. 1997, *A&A*, 317, 793  
 Shakura, N. I., & Sunyaev, R. A. 1973, *A&A*, 24, 337  
 Shapiro, S. L., & Lightman, A. P. 1976, *ApJ*, 204, 555  
 Shimura, T., & Takahara, F. 1995, *ApJ*, 445, 780  
 Tanaka, Y., & Lewin, W. H. G. 1995, in *X-Ray Binaries*, ed. W. H. G. Lewin, J. van Paradijs, & E. P. J. van den Heuvel (Cambridge: Cambridge Univ. Press), 126  
 Thorne, K. S. 1974, *ApJ*, 191, 507  
 Zhang, S. N., et al. 1997a, *ApJ*, 479, 381  
 ———, 1997b, *ApJ*, 477, L95